The Formation Control Testbed

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Abstract—Terrestrial Planet Finder (TPF) is a space telescope mission which will perform spectral analysis of the infrared emissions from extrasolar planets, and which will search for carbon-based life on such planets. One configuration being considered for this mission is a stellar interferometer with several collectors and a combiner on separate spacecraft flying in a tightly controlled formation. The distance to earth for this mission will be sufficiently great that having ground in the loop for reconfiguration or collision avoidance maneuvers will be impractical. Moreover, because of constraints in the orientation of the spacecraft relative to the sun, limitations on the field of view of relative range and bearing sensors, and restrictions on the orientations of thrusters, both the attitude and the relative position of each spacecraft in the formation must be taken into account in the event of a temporary sensing or control fault during maneuvers. These maneuvers include initial deployment of the formation, reconfiguration, and collision avoidance maneuvers. The Formation Algorithms and Simulation Testbed (FAST) and the Formation Control Testbed (FCT) at JPL are being built to simulate and demonstrate 6 degree of freedom, autonomous formation flying and reconfiguration for TPF. The testbeds are complementary. Control algorithms simulated in the FAST will be tested in the FCT in order to validate the FAST.

This paper describes the design and construction of the Formation Control Testbed. The FCT consists of three robots navigating on an air bearing floor, propelled by cold gas thrusters. Each robot contains an attitude platform supported on a spherical air bearing which provides three rotational degrees of freedom. The sixth degree of freedom, vertical translation, will be provided by a powered vertical stage, actively controlled to provide a simulated zero-g environment for the attitude platform.

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1. INTRODUCTION

The Formation Control Testbed is one of a family of four testbeds that will demonstrate critical aspects of formation flying technology for TPF, the Terrestrial Planet Finder [1]. Of these testbeds, the Formation Sensor Testbed (FST) [2] will demonstrate a microwave-based formation acquisition sensor. The Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) [3] will demonstrate formation acquisition and reconfiguration in the zero-g environment of the international space station. The Formation Algorithms Simulation Testbed (FAST) [4] demonstrates real-time control in a distributed formation simulation environment.

FCT consists of three autonomous robots, navigating in a 40' diameter, circular room on an air bearing floor. As shown in Figure 1, each robot consists of a lower assembly, the translation platform, and an upper assembly, the attitude platform. In operation the translation platform floats on three air-bearing feet supplied with float gas from air tanks on the translation platform. The same tanks also supply a spherical air bearing which supports the attitude platform. A special floor is used to provide the necessary level of flatness so that the robot moves in a manner substantially unaffected by gravity. Air bearings such as these have been in use in space simulator applications since the late 1950's (see [5] for an excellent overview). JPL and UCLA have also collaborated on a recent testbed [6].

The combination of the two linear degrees of freedom provided by the air bearing feet of the translation platform and the three rotational degrees of freedom of the attitude platform give the attitude platform the freedom to move virtually without friction in five degrees of freedom. A vertical stage, to be fitted to the translation platform between the air bearing feet and the spherical air bearing will provide a sixth degree of freedom for the attitude platform.

The role of FCT in the family of TPF testbeds is to validate the simulation-based FAST and to demonstrate precision formation flying. FAST will simulate the dynamical behavior of FCT using detailed models of the FCT robots, and the simulation behavior will be compared with that observed in FCT operation. Agreement between FAST's simulations and FCT's observed behavior will provide confirmation of the fidelity of the FAST simulation environment.

FCT will also demonstrate precision formation control of the kind required from the TPF spacecraft. The three robots will fly in a triangular configuration, maintaining relative range to +/- 7 cm, relative bearing to +/- 85 arc minutes; and attitude in the room frame to +/- 7 arc minutes. These performance requirements are comparable to those required from TPF in order for the interferometer to be able to acquire lock.

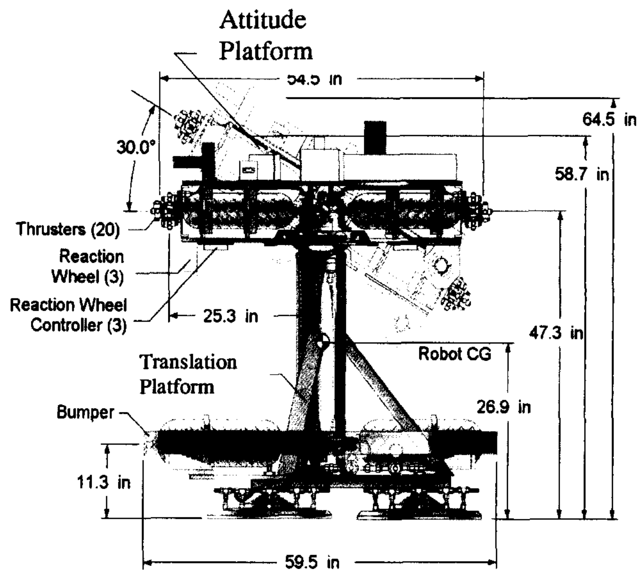

Figure 1: Robot design

The remainder of this paper describes the structure and function of the translation platform and the attitude platform, and of the air bearing floor on which the robots float. It also describes constraints taken into account in the design of the attitude platform and its reaction wheels, and a section is devoted to a description of the robot avionics.

2. TRANSLATION PLATFORM

Each of the three feet of the translation platform consists of an aluminum disk with 16 pairs of equally-spaced air jets in its lower surface. These jets are supplied with compressed air at a pressure of 50 psi, and in turn supply the gap between the foot and the floor with a cushion of air upon which the foot floats. Testing and analysis have shown that for the loading generated by the weight of the robot, and a fly height of 0.003", each foot consumes 2.5 standard cubic foot per minute of air, or 5.2 kg per hour.

The spherical air bearing which supports the attitude platform consists of a ball segment and a cup. The cup is supported by the translation platform, and the ball segment, supported on a cushion of air by the cup, supports the attitude platform. The cup of the spherical air bearing contains 8 evenly spaced air jets which are supplied with compressed air at 50 psi and which supply air to the bearing gap. When the supply pressure falls below 30 psi, to protect the bearing surfaces from direct metal-to-metal contact, the cup retracts into a cylindrical protective bumper sleeve. This assembly is shown in Figure 2.

Air for both the spherical air bearing and the linear air bearing feet is stored at a pressure of 4500 psi in 8 tanks. These tanks (Structural Composites ALT 604) are aluminum tanks externally reinforced with a composite plasticimpregnated fiber material, and provide excellent float gas storage capacity per unit tank weight. The pressure is regulated down to the 50 psi required by the air bearings in two stages, with the first stage reducing the pressure to 300 psi and the second reducing it to 50 psi. Safety pressure relief valves are fitted between the tanks and the first stage regulators, between the first and second stages, and between the second stage and the air bearings. The first set of safety valves protect the system from tank overpressures, which could occur in case of over-filling or fire, and the remainder of the pressure relief valves protect downstream components from regulator failures. The high pressure fill port is fitted with a check valve to prevent high pressure air from escaping when the fill line is vented or detached. This check valve also supports remote filling of the robot for safety. Gauges are fitted at the tanks to monitor the level of float gas, and downstream of each regulator to monitor the operation of the regulator.

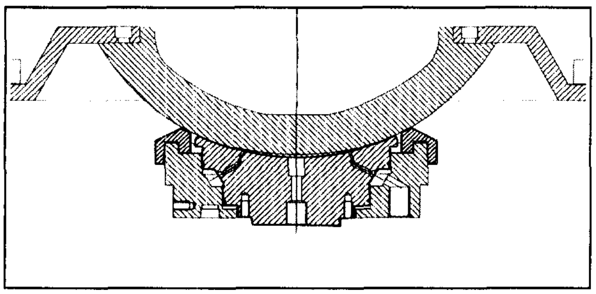

Figure 2: Spherical Air bearing cross-section

A bumper is fitted to the perimeter of the translation platform to protect the robot in case of collision with other robots or with the railing at the edge of the floor.

3. Attitude Platform

The attitude platform (see Figure 3) consists of two flat plates, propellant tanks supported between the plates, avionics mounted on top of the upper plate, reaction wheels and batteries mounted below the lower plate, and cold gas thrusters mounted at the edges of the plates. The ball segment of the spherical air bearing, which supports the attitude platform, is mounted to the lower plate.

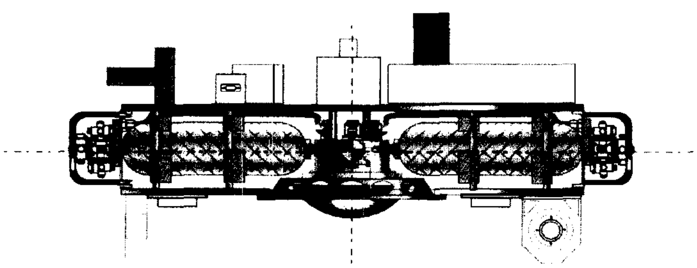

Figure 3: Attitude Platform, side view

The cold gas thrusters (Guidance Dynamics Corporation model #40600) are solenoid-valve actuated direct action thrusters (see Figure 4). The amount of thrust generated when the valve is open is adjustable in the range of 0.5 N to 22 N by adjusting the supply pressure or changing the nozzle diameter. The minimum impulse generated by these thrusters corresponds to a valve-open duration of 6 ms.

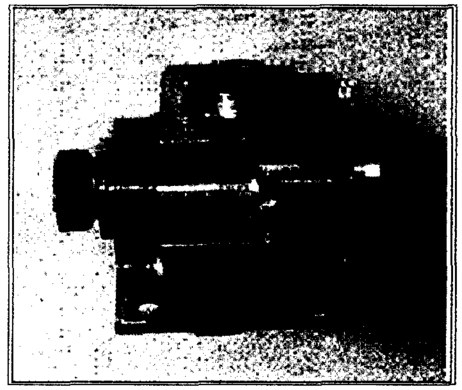

Figure 4: Cold Gas Thruster

Supply gas for the thrusters is provided by a two-stage regulator system in which the first stage is a passive mechanical regulator and the second stage is an active electro-pneumatic system consisting of a solenoid valve, a plenum supplied by the valve, a pressure transducer monitoring the pressure in the plenum, and feedback electronics which control the opening and closing of the solenoid valve in such a way as to keep the plenum pressure within the specified range. This system is capable of regulating pressure to an accuracy of 1%, over the full range of supply pressures and gas flow loads. This is significantly better than the performance of typical mechanical regulators, the output pressure of which typically varies by 10% as the supply pressure changes over its normal operating range.

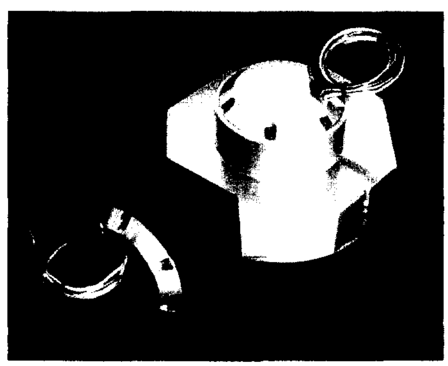

Figure 5: Reaction Wheel

Each of the three reaction wheels (Guidance Dynamics Corporation model 10460 – see Figure 5) consists of a 5 pound brass flywheel supported in precision bearings and driven by a frameless brushless DC motor. Each wheel is capable of delivering 0.2 Nm of torque to the attitude platform, and of storing 1.4 Nms of angular momentum.

4. Attitude Platform Balance

A number of factors constrain the sizing of the thrusters and the reaction wheels, and impose constraints on the tolerable floor slope and attitude platform imbalance. For similarity to TPF, in which the firing of thrusters may disturb science measurements, we require that the robots be able to perform precision formation flight without firing their thrusters more than once every 6 second. We allocate 4/7 of the allowable precision formation flying error to control dead-banding, i.e., the control dead bands are +/- 4 arc minutes in attitude and +/- 4 cm in translation.

These constraints lead to fairly tight requirements on the position of the center of mass of the attitude platform relative to its center of rotation, i.e., the center of the spherical air bearing. Any horizontal spatial separation between these two points will lead to a gravity torque about the center of rotation. If the firing of a thruster every 6 seconds is to hold the attitude platform at a desired attitude to within +/- 4 arc minutes, then between thruster firings the angular acceleration due to the gravity torque must not exceed 1.8 arc minutes/s^2. For a transverse moment of inertia of 18 kg m^2, this corresponds to a gravity torque of 0.005 Nm. This torque in turn corresponds to a maximum horizontal distance between the center of rotation and the center of mass of 0.003 mm. Moreover, the center of mass of the propellant must also be located close to the center of rotation, so that as the propellant is depleted, the center of mass of the attitude platform does not move outside of the bounds specified above. For a propellant mass of 11.4 kg, a gravity torque of 0.005 Nm corresponds to a position error of 0.045 mm.

The reaction wheels are sized so as to allow the robot to maintain attitude control without thruster firing for 360 seconds. For a gravity torque of 0.005 Nm, and assuming that the wheels are pre-biased with angular momentum in the desired direction, this corresponds to a minimum reaction wheel size of 0.9 Nms.

5. Floor

The robot's finite propellant capacity and the requirement of being able to operate for one hour on one charge of propellant leads to a floor slope requirement. The robot's thrusters generate thrust at a specific impulse of 55 seconds using the compressed air propellant, and of the 11.4 kg of propellant stored in the attitude platform, we allocate 40% to floor slope compensation. For a robot mass of 358 kg and a run time of one hour, this leads to a maximum floor slope of 160 μ radians, or 33 arc seconds.

A top view of the floor, which is the lower surface for the linear air bearing, is shown in Figure 6. The floor is composed of multiple rectangular panels tiled together and cross-tiled with 5.5mm thick annealed glass.

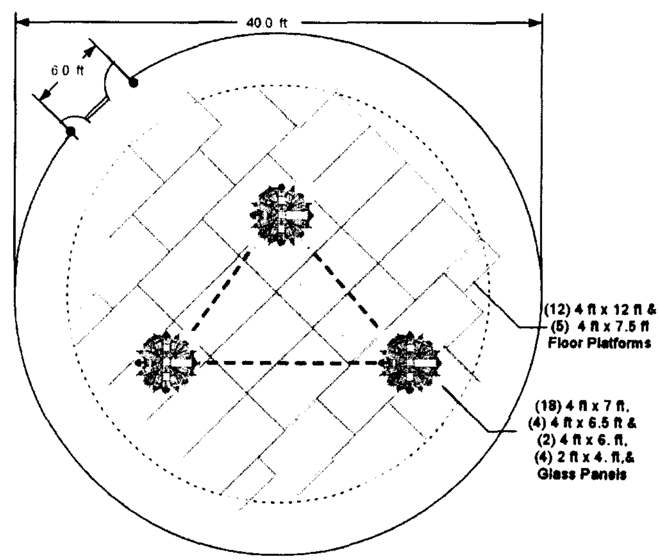

Figure 6: Top view of FCT floor with 3 robots

Each panel (see Figure 7) consists of a lower frame supported on coarse leveling screws, an upper frame supported on the lower frame on fine (compound) leveling screws, and an aluminum plate bolted onto the upper frame.

The upper frame assembly including the aluminum plate is Blanchard ground to an overall flatness of +/- 0.001", as shown in Figure 8.

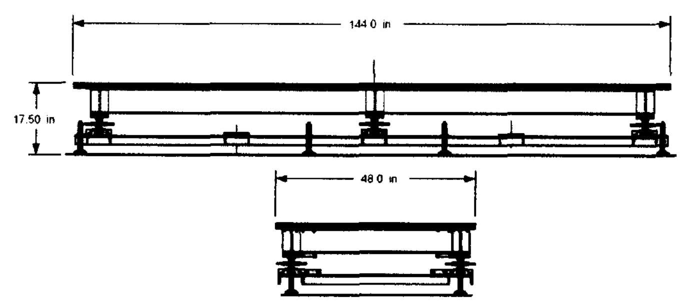

Figure 7: Floor panel construction

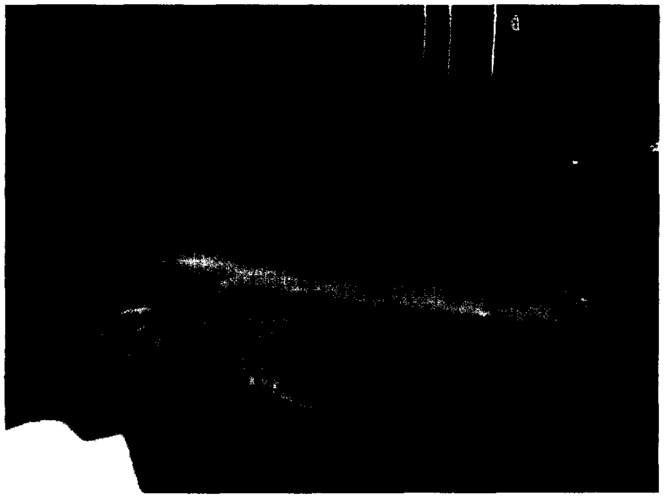

Figure 8: Blanchard grinding of floor panel

We have measured the flatness of two prototype floor panels using a Leica 3D Laser Tracking System. In performing these measurements, a retroreflector is placed at various points on the surface to be measured. The laser tracker tracks the position of the retroreflector, and saves the coordinates to a file.

Figure 9 shows contour plots generated by fitting a two-dimensional spline to such a set of measurements for one of our prototype floor tables. We estimate the maximum slope for this table to be 150 +/- 50 μ radians. This is comparable to our requirements, but we believe that most of the observed slope is due to noise in the laser tracker, the accuracy of which is +/- 0.001", corresponding to slopes easily exceeding our requirements over the relatively tight grid of data points used. System-level tests in which an air bearing is flown across the floor and the transverse force or acceleration is measured will provide more conclusive evidence as to the performance of the floor.

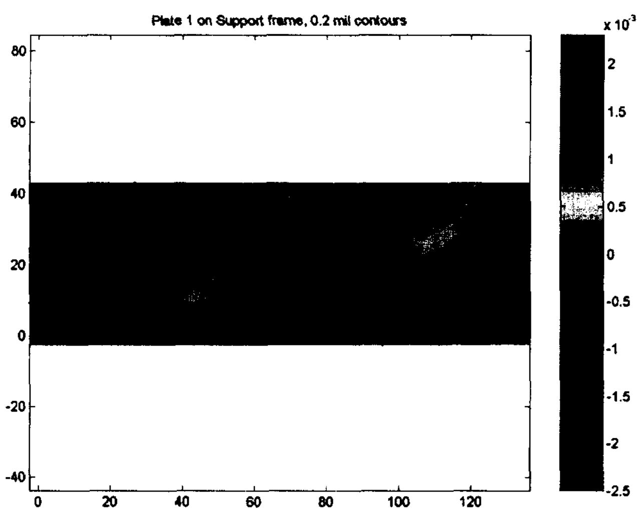

Figure 9: Floor panel surface contours

6. AVIONICS

A block diagram of the robot avionics is shown in Figure 10. A compact PCI chassis houses the central computer (a PPC 750),99 the versatile I/O card (DAQ1), and the inter-robot communications card (DAQ2). The DAQ1 card provides an interface to all of the robot sensors and actuators, including a Crossbow IMU 400 inertial measurement unit (IMU), thrusters, reaction wheels, and two purpose-built sensors, the Celestial Sensor, and the Formation Sensor. The Celestial Sensor consists of an infrared Position Sensitive Detector (PSD) at the focus of a wide angle lens. The lens images LED beacons on the ceiling of the room onto the PSD. The LED beacons are pulsed in a predetermined sequence, and the Celestial Sensor estimator, which runs in a dedicated microcontroller, calculates both the attitude of the attitude platform and its position in the room from the PSD measurements. The Formation Sensor is used to measure the relative range and bearing of another robot within the sensor's 10-degree half-angle field of view. Range measurements are done by measuring the time of flight of a modulated infrared beam which is sent back by a repeater on the target robot; bearing is measured by a lens and PSD combination, similar to the one used in the Celestial Sensor.

The algorithms in the central computer run at 1 Hz, and are invoked by a task whose execution is controlled by a delay timer mechanism provided by the Real-Time Operating System (RTOS). The sensors on the robot operate asynchronously. For this reason, sensor readings must be time-tagged as they are delivered to the central computer for processing. The Celestial Sensor and Relative Sensor both assign time tags to all data sent to the DAQ1 card. Time on the DAQ1 card is synchronized with time on these peripherals at startup. To synchronize, the DAQ1 card sends out a pulse indicating mission time 0. Additional sync pulses are sent out at a 1 Hz rate after startup to resynchronize in case of clock drift between the DAQ1 card and the peripherals. Time tags are assigned to the IMU data at the time these data are received by the DAQ1 card. The central computer communicates with the DAQ1 card via memory mapped I/O across the compact PCI bus; the DAQ1 card contains a semaphore-controlled dual-port memory for this purpose. Mission time, as defined by the DAQ1 card, is stored in this memory, as well as sensor readings. Writes to the appropriate memory locations trigger thruster firing or changes in reaction wheel torque.

7. STATUS AND PLANS

Presently, detailed design of the robot, floor and avionics is complete, and construction of the first robot is beginning. The construction of additional robots and of the floor is planned in phases such that all three robots will be complete and demonstrating formation flying maneuvers in mid-2006.

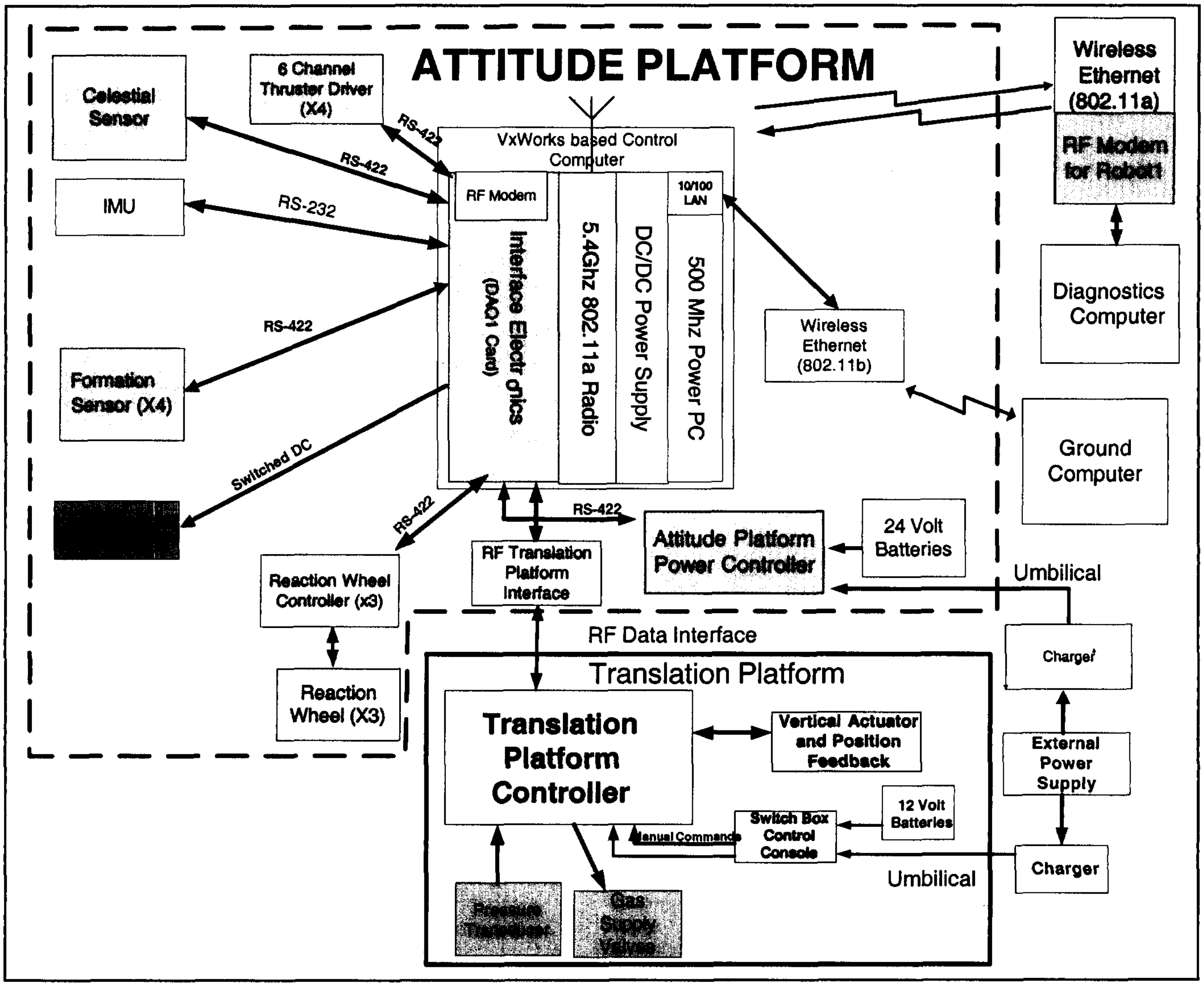

Figure 10: Avionics Block Diagram

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